LGC OPEN-SOURCE: A STRATEGY TO SHARE ADJUSTMENT SOFTWARE AND ALGORITHMIC DEVELOPMENT

G. Kautzmann*, J. Gutekunst, F. Klumb, P. Elson, CERN, Geneva, Switzerland

Abstract

LGC (Logiciel Général de Compensation) is a software that computes position estimates and associated statistics based on observations obtained by CERN surveyors. Since the mid-1980s, LGC has been a crucial tool to perform geodetic computations in various contexts - from simple levelling campaigns to advanced monitoring projects. The CERN Geodetic Metrology group continues to maintain, improve, and modernize LGC. Over time, LGC has achieved maturity and stability thanks to extensive testing and continuous improvements.

Up to now, LGC has been a proprietary software, with its use restricted to CERN and rarely licensed to outside entities. Driven by growing interest from external partners, this paper details the beginnings of the journey for transitioning LGC to an open-source platform. By open-sourcing LGC, we aim to ensure its long-term viability and quality, encourage contributions from a wider user/developer base, and foster community mutual assistance around accelerator alignment problems. We detail the motivation behind this initiative and the role played by the newly established Open Source Program Office (OSPO) at CERN for facilitating open-source licensing and distribution.

INTRODUCTION

Surveyors depend on robust computational tools to analyze their measurements and associated statistics. These tools range from commercially available software to in-house projects. At CERN, surveyors utilize numerous observation types coming from a diversity of instruments, spanning from traditional instruments like laser trackers or total stations to more specialized devices such as offset systems to stretched wire. Increasingly, they also employ sensor-based systems like Wire Positioning Systems (WPS) or Hydrostatic Levelling Systems (HLS). The "Logiciel Général de Compensation" (LGC) calculates the 3D positions of objects, typically points, through least-square adjustments of various geospatial observations, along with the associated statistical indicators. It was specifically developed and has been continuously maintained since the mid-1980s, ensuring it meets the requirements of CERN's surveying operations. LGC is an important part of a comprehensive ecosystem of software tailored to support CERN's surveying needs. This ecosystem brings together LGC and associated pre- and post-processing tools. It also comprises a user interface, called SurveyPad [1]. LGC is integrated into the measurement acquisition software [2], has input files written by the CERN Survey Database via its interface GEODE [3], and is being more and more used within monitoring systems [4].

Historically, the LGC software has been under proprietary licensing. Two European seminars, held in summer 2023 and spring 2024, with the accelerator surveying community [5] demonstrated a strong need and interest for a common adjustment software solution. It was decided to explore the possibility of making LGC available as open-source software. This decision coincided with the establishment of CERN's Open Source Program Office (OSPO) in early 2024, designed to support the transition of in-house technologies, such as LGC, to open-source platforms. This paper begins by detailing the history, key functionalities, and recent major developments of LGC. It then outlines the transition of LGC to an open-source platform, discussing the motivations behind the move, the strategic approaches adopted, and the anticipated benefits for both CERN and the geodetic community. We also explore the initial steps taken, the role of CERN's OSPO in this transition, and the broader implications and challenges foreseen.

LGC OVERVIEW

LGC has been a cornerstone of CERN's geodetic data analysis since the mid-1980s. Its primary purpose was to provide a robust toolkit for processing CERN's geospatial data, accommodating various measurement types utilized by surveyors at the time [6]. Initially developed in Fortran77, LGC was capable of processing data from theodolites, distance meters, and horizontal wire offsets, through least-square adjustments within a 3D coordinate system. This system was either locally defined or using local horizontal and geodetic reference surfaces established at the time for the CERN site. Over the years, the program has evolved substantially, incorporating new observational models and analysis tools. In the late 2000s, LGC underwent a major transformation with a complete rewrite in C++ [7], introducing object-oriented programming, enhanced stochastic models, and additional observation equations. A C++ software library, called SurveyLib, was also created to provide, amongst others, mathematical concepts, spatial objects, least-square routines, and geodetic transformations. For example, it houses a simple length definition or an adjustable position in space with complete attributes and methods to be used for surveying software. SurveyLib has become a fundamental component in most C++ software developed for CERN's surveyors and remains actively maintained. The introduction of LGC version 2 in 2016 [8] marked the latest significant evolution, featuring additional observation models, especially an abstraction of small camera sensors, and modifications in the input format to accommodate default observation stochastic models. It also introduced the "*FRAME" keyword, allowing the definition of a hierarchy of reference systems. Each

* guillaume.kautzmann@cern.ch

system can contain points or observations. Each "*FRAME" object is represented by a 7-parameter Helmert transformation where each parameter can be estimated or kept fixed during the least square process, at the discretion of the user. The nearly 40 years of LGC's existence have been made possible through the efforts of a large number of people. Many developers have contributed, ranging from entry-level surveyor trainees to IT specialists. CERN surveyors have tested and suggested new features and project requirements have continually pushed the boundaries throughout these years.

As of 2024, the current version 2.7.0 supports twenty observation models, originating from Total Stations, Laser Trackers, HLS, WPS, inclinometers, levelling systems, distance meters and simple abstractions for cameras and coordinate measurement machines. It allows for various point definitions, from completely free-floating to fixed control points without parameters to estimate. Users can introduce multiple constraints on network parameters or options to generate diverse output formatting and analytical indicators, such as calculating relative errors between selected points. The software operates only 3D computation in a Cartesian XYZ system, but due to the extensive scope of the CERN accelerator complex, LGC manages three local geoid models [9]: a simple spherical model, the CERN Geoid 1985 (CG1985) and 2000 (CG2000). The geoid models are, for instance, used in the observation made by a Total Station to establish its vertical vector in the CERN Coordinate System (CCS) expressed in XYZ. Computations in LGC can be launched either with predefined control points and constraints or through a free adjustment mode that does not require fixed parameters. In the latter case, dynamic constraints are added on the network centroid in translations and momenta. LGC embeds simulation tools to perform prospective work.

Geodetic Metrology Software ecosystem

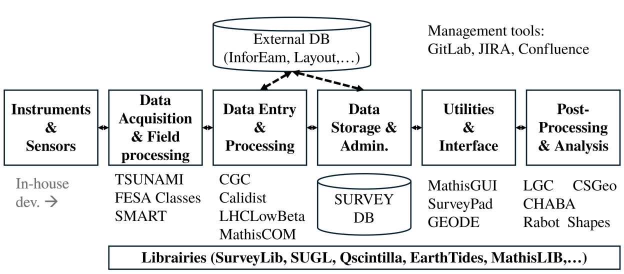

Figure 1: Geodetic Metrology Software ecosystem

Figure 1 maps out the projects currently being developed by the Geodetic Metrology group at CERN. In the field, surveyors employ TSUNAMI [2] and SMART [10] software for capturing and analyzing geospatial data. This data is subsequently archived in the Survey Database via its interface GEODE. Both GEODE and the field acquisition software can create files suitable for data-processing software: LGC, CHABA, Rabot, Shapes and CSGEO. CHABA computes an optimal 7-parameter Helmert Transformation between point clouds via least squares. Rabot [11] is used for accelerator smoothing operations. SHAPES does geometrical shape fitting on point sets. CSGEO is used for geodetic transformations between reference systems. Except for Rabot, which is coded in Python, all data-processing applications are developed in C++ and utilize SurveyLib. SurveyPad [1] serves as the unified interface for all these processing applications.

LGC Usage

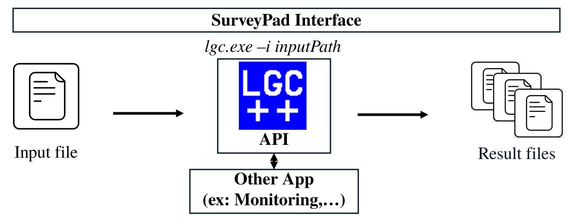

Figure 2: Ways to use LGC

On Windows or Linux, LGC operates simply as an executable that processes a formatted text file (Fig. 2). This file contains all computation options, the a priori values of parameters (typically 3D point positions), all constraints, and all observations with associated values to define the stochastic model. Initiated via command line without a user interface, LGC conducts least squares adjustment, outputting results in text files or issuing error notifications. Errors can come from several sources such as formatting problems or divergent computation. The specifics and number of result files can be customized through keywords in the input file. Since mid-2023, LGC also supports a serialized JSON output format and the first iteration of an application programming interface (API). In its integration within TSUNAMI, LGC acts as the primary computation tool for positioning, such as determining the position of a Laser Tracker within the network. TSUNAMI and GEODE can both export files in a format readable by LGC. LGC can then generate files to update the current position of accelerator or network points stored within the Survey Database.

LGC is used for a wide spectrum of surveying activities, ranging from simple alignment to advanced R&D. The new versions have opened up possibilities for beam level alignment methods [12], rigorous integration of levelling systems into 3D computations [13], complex sensor-based monitoring [14, 15], integration into automated measurement processes [16], and is already used and been prepared for Future Circular Collider studies [17, 18].

LGC major new features

Data serialization LGC traditionally generates unstructured text-based result files. With the release of LGC v2.6.0 in June 2023, it has been enhanced to support data serialization in JSON format. This functionality is provided by a serialization class implemented in the overarching SurveyLib Library. The base JSON file now contains the data structure utilised within LGC. It includes the input and result data. Large objects, such as the covariance matrix, are not serialized by default to avoid bloated JSON files, slow file access, and potential memory issues on computers. They can be included in the serialization if needed by enabling an option. In addition, some relevant computations otherwise complicated to do in post-processing are also part of the JSON object. For instance, typically, surveyors analyze precision in a common root reference system. Points and their precision can be expressed in other reference systems. The computation of the precision of such point in the root system is done within the LGC environment and available in the base JSON file. This feature simplifies the development of new functionalities and automation processes, reducing effort and enhancing the robustness of data parsing. For example, the JSON export is now used to generate user-friendly and dynamic HTML result reports (Fig. 3), leveraging modern web technologies that enable dynamic table display with sorting and plotting options. This improvement was achieved by developers who did not need to engage directly with the LGC C++ codebase, thus bypassing the steep learning curve associated with coding in LGC and allowing contemporary technologies usage, such as web programming or Python scripting. A potential long-term enhancement for LGC could involve the development of a deserialization feature. This would enable the software to launch directly from a JSON file, streamlining the creation of input files by making them machine-readable. Currently, there is no plan to implement this feature in the near future.

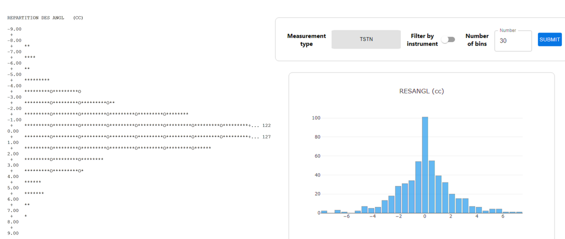

Figure 3: An histogram displayed in the historic text file (left) and in the HTML report (right)

LGC API The LGC API provides a series of methods to read an LGC input file, update measurements or parameter statuses, launch analyses, and extract results and associated statistics. This development was triggered by the Full Remote Alignment System (FRAS) [4] project and has been in use for tests since late 2023. The method set provided by this library is specifically tailored to meet the needs of the FRAS project and is expected to evolve to accommodate the requirements of new and ongoing projects. This project also involved drastic improvement in computation speed and robustness available for all new versions and described in [4]. Currently, the LGC library requires a formatted input file. The ultimate goal is to unblock file-less operation. Configuration would instead be achieved entirely through direct interactions with the API. Users would be able to dynamically set all necessary parameters and options by calling methods. This approach would streamline processes by removing the intermediary step of file creation. It would make the system more adaptable to real-time adjustments and easier to integrate with other software tools or systems. The library is designed for easy interfacing and is available as a "dynamic link library" (DLL) for Windows, or a "dynamic shared object" for Linux. For instance, the DLL can be interfaced with Python to leverage its extensive analytical tools and rapid prototyping capabilities, enhancing the accessibility and usability of LGC for both surveyors and developers.

LGC Quality Assurance (QA)

For QA and project management, the current LGC development team relies on standard tools commonly used within and outside CERN. JIRA [19] serves as the principal platform for project management and ticketing. It facilitates the submission of tickets that highlight issues or requests for new functionalities. Additionally, direct engagements, such as meetings with surveyors, are regularly organised. Obtaining feedback directly from end-users ensures that software development is tightly aligned with the operational demands faced by CERN's survey teams. The development team employs GitLab for software development, version control, and continuous integration/continuous deployment (CI/CD), customized specifically for CERN's settings [20]. This DevOps platform manages all code repositories related to surveyor software, including LGC. Developers manage their tasks by initiating branches for each feature, typically corresponding to a specific JIRA ticket. Comprehensive code reviews, performed by LGC specialists and IT professionals, are carried out when a feature is to be merged into the main development branch. The reviews are essential to preserve code quality and ecosystem compatibility. Updates to the master branch are synchronised with the biannual release scheduled during spring and autumn to precede CERN's technical stops. Each release undergoes thorough testing using a set of approximately 150 LGC input files representing various use cases or calculation edge cases. These files are manually inspected to ensure output consistency and minimal or explainable impact on results. The CI/CD processes run on dedicated CERN OpenStack [21] virtual machines for Windows, and on Kubernetes container images for Linux environments. The CI/CD pipeline automatically triggers a suite of unit and functional tests that comprehensively cover new and existing features. LGC and SurveyLib codebases have been developed over nearly four decades and not all parts are covered by automated tests. There is a strong emphasis on rigorously testing all new code and functionalities. For reference, the LGC main software, including the test protocol, comprises over 30000 lines of C++ Code, while the SurveyLib Library is just shy of 50000 lines of C++ code.

OPEN-SOURCING

Intermittent internal discussions to pass LGC to an open-source license have taken place for nearly a decade. The discussions recently intensified following feedback from survey groups at other European accelerator facilities, who expressed a strong desire for a shared least squares adjustment tool specifically tailored to their unique needs. This enthusiasm was displayed during seminars in 2023 and 2024 [5]. Up to now LGC was occasionally licensed to external partners through CERN's Knowledge Transfer group. While functional, this licensing model did not fully encourage broad adoption or active contribution from these partners, leaving many hesitant to engage deeply. Transitioning to an open-source approach is perceived as a more reassuring and encouraging strategy to foster deeper collaboration and active participation. Following the adoption of the CERN Open Science Policy [22] at the end of 2022, an Open Source Program Office (OSPO) was established in early 2024, providing an additional incentive to move LGC to open-source. The OSPO now provides organisational support for this transition.

By transitioning LGC to an open-source model, the CERN Geodetic Metrology group aims to tap into the collective expertise of a global community, which could drive innovation through the rapid integration of enhancements, new features, and bug fixes to keep the software relevant and effective. Furthermore, open-sourcing LGC is intended to facilitate the building of a robust community of users and contributors. Engaging this community is seen as crucial for steering the software's evolution by adapting it to a wider array of applications, thereby enhancing its robustness and versatility. Additionally, moving to open source aims to ensure the long-term development of LGC by enabling the potential inclusion of external resources or individuals already familiar with the software into the core development team. Open sourcing is envisioned to maintain the integrity and continuity in the developments of LGC.

From an educational perspective, the benefits of making LGC open-source are significant. It will allow academic institutions to incorporate this tool into their curricula, providing students with hands-on experience in surveying and data analysis. This approach not only enriches the educational experience but also promotes research and development as students and researchers contribute to a project with real-world applications in science and engineering.

Open-sourcing LGC enhances transparency, which is fundamental in scientific research, building trust in data processing and results through wider benchmarking and cross-comparison initiatives with other solutions [23], further enhancing its credibility and utility.

Role of the OSPO

The CERN OSPO was established in early 2024 to provide consistent organizational practices for both open-source software and hardware initiatives at CERN, as detailed in its mandate [24]. The OSPO is committed to promoting CERN as an active contributor to open-source development and ensuring CERN's due diligence in open-source engagements. However, it's important to note that while the OSPO has set ambitious goals, many of its processes are still in the initial stages of development and not all are fully operational. The OSPO membership is drawn from across the organisation on a part-time basis, ensuring that there is CERN-wide representation.

Internally, the OSPO's role comprises a wide array of responsibilities. It consults, advises, and trains the CERN community on best practices, tools, licenses, and developments related to open-source projects. This includes providing implementation guidance for CERN's Open Science Policy components and offering recommendations for open-sourcing. The OSPO also develops guidelines on various technical aspects of sharing code and designs, including where to host, what services to use, appropriate use of CERN infrastructure, and general tooling for open source such as license compliance checks and test setup configurations. Additionally, it processes incoming requests for open sourcing following established procedures, and facilitates due diligence for the dissemination of open source materials. Moreover, it advises CERN management on open-source matters that impact the organization.

The OSPO manages a public catalogue of CERN's open-source projects, accessible from the OSPO website. It guides interested external parties to opportunities, projects, and experts at CERN through this public catalogue, events, external communications, and the website. The office also facilitates and publicizes CERN's contributions to open source initiatives and enhances CERN's image as an "Open Source lab". It handles also external inquiries related to open-source projects at CERN, ensuring that the organization remains responsive and engaged with the broader community.

The LGC transition does not benefit from all processes already being well-established. It serves as a pilot project for the OSPO on how to deal with open-sourcing software developed within the CERN premises over a long period of time. It will provide insights and experience to help refine the OSPO's future strategies and operational approaches.

Implementation Strategy

Preparation and Planning Following recent European Survey Seminars [5], a quick transition to make LGC, SurveyLib, and SurveyPad available to the wider community was planned. Working with the CERN OSPO, an extensive audit of LGC and SurveyLib's codebases is underway to resolve any licensing issues and ensure compliance with open-source guidelines. This verification that all components, including third-party libraries, are suitable for public distribution, is expected to be complete by Autumn 2024. Accessibility and security concerns are also being addressed regarding the current workflow and use of the Gitlab and JIRA environment. Despite extensive existing documentation for LGC's functionalities and models, enhancements are necessary. The user manual has received particular attention. The documentation improvement for the stochastic and observation model are ongoing. Setting up community platforms like a website, forum, and chat is planned, along with a clear development roadmap. Promotional efforts, including this paper, aim to gather initial feedback and prepare for the launch.

Launch and Promotion The launch will introduce LGC and SurveyLib as open-source, accompanied by a distributable version of SurveyPad. Initially, SurveyPad binaries will be available to ease immediate use and promote the adoption of LGC. Providing only LGC binaries is also being considered to allow external users to assess whether the software is fit for their needs without full open-source access. LGC should be externally available later this year after the LGC version 2.8.0 release. Outreach efforts will follow the release. LGC developers and experienced users will provide training and support. An online training sessions is planned by this paper's authors for example. This outreach will extend to academic and research institutions to foster partnerships. No governance or licensing model is yet defined, but the initial governance is likely to be strictly controlled by the CERN Geodetic Metrology Group, with plans to evolve.

Growth and Sustainment Post-launch, LGC will enter an iterative development phase, with updates considering community feedback to keep the software relevant and effective. A strong community management system will be essential to moderate discussions, manage contributions, and maintain a constructive community environment with regular roadmap updates. The initial direct contributions to LGC and SurveyLib are expected to be minor, with more substantial contributions expected to come from creating post- or pre-processing tools for LGC. These contributions are hoped to be shared openly and widely. Over time, it is hoped that contributions to the core software will increase, requiring review by experienced developers before integration.

Foreseen challenges

Transitioning LGC to an open-source framework presents several challenges that the CERN team must navigate carefully to ensure a successful and secure implementation. The core development team is small, and hence patience and understanding from the community will be crucial as we navigate the learning curve of rolling out open-source LGC.

One of the primary challenges is selecting an appropriate open-source license that aligns with the dependencies currently used in LGC and SurveyLib. The license must satisfy the legal frameworks while being flexible enough to encourage widespread adoption and contribution. On the management level, a GNU General Public License (GPL) is currently recommended [25] and is under review by the OSPO. For LGC, the goal is to align with CERN's mission to contribute to society and industry, facilitating industry adoption, collaboration, and contribution. Ongoing discussions between the developers and OSPO aim to refine these licensing decisions.

Another significant challenge involves managing access to the infrastructure in place, specifically the platforms that host the software and handle project management tools such as GitLab and JIRA. Currently, the LGC repository resides on CERN's GitLab, accessible only to users with CERN accounts. This setup poses questions about how to facilitate contributions from external developers. The official OSPO recommendation is to migrate to an external hosting platform (for example GitHub) and to mirror the project into CERN GitLab as a long-term back-up strategy. The licensing for JIRA, deeply integrated into the current workflow for ticketing and user requests, also requires attention. We need to ensure that the integration between JIRA and the hosting platform supports seamless project management. Solutions for inclusive discussion and ticketing must be found to welcome wider community participation. These migrations should be accompanied by a refactoring of our quality assurance workflows and runner configurations for CI/CD. Additionally, the project owner must manage the roles of each external contributor, ensuring due diligence is maintained. This includes potentially implementing a "Developer Certificate of Origin" (DCO) and maintaining an updated list of authors. This approach will safeguard the integrity of contributions and streamline project management across platforms. These migrations are the current limiting factor for the timeline in the LGC open-sourcing, particularly with the CI/CD infrastructure. While not all components are essential from the beginning, it is important to address these factors early in the migration process to ensure smooth integration and effective deployment of the new systems.

To encourage community engagement, we plan to establish multiple communication channels. These include a dedicated website, a forum for discussions, and live chat support. They will facilitate not just developer interactions but also fostering a space for exchanges between new and experienced users.

Initially, the governance of LGC will remain strictly under CERN control, but it is anticipated that this will evolve into a more inclusive governance model. This evolution will ensure that LGC continues to benefit from active community contributions and collaboration, reflecting a shared commitment across the broader scientific community.

It is essential to outline a clear and transparent roadmap for LGC's development. While the initial focus may not be on direct contributions to the core code, we foresee significant involvement in developing the ecosystem around LGC. For example, creating tools that allow data from commonly used industry software like Spatial Analyzer [26] to be easily converted into LGC-ready formats could be a valuable external contribution.

The aim is also to openly distribute the LGC GUI, Surveypad. Without its numerous ease-of-use features, working with LGC can be challenging and unappealing. SurveyPad could play a crucial role as the central hub in this ecosystem. It currently supports a scripting strategy that performs various pre- and post-processing tasks. Scripts can be written in any language, with Python preferred for its ease of use. Expanding SurveyPad's capabilities to allow users to download and execute scripts from a communal repository could significantly enhance the software's utility.

The steep learning curve required to actively develop for LGC and Surveylib cannot be overlooked. New developers typically require around six months to become proficient with LGC's C++ environment, with full autonomy taking up to a year. Any changes in LGC can have wide-reaching effects across its ecosystem, impacting associated processes and tools. Managing these changes carefully is crucial to prevent disruption and encourage ongoing development within the community.

CONCLUSION

This paper has outlined the transition of CERN's main survey and alignment software, LGC, towards an open-source model. Open-sourcing should provide a durable and reliable least square adjustment solution for the whole of the accelerator surveying community, gathering new ideas and providing a common platform to enhance collaboration. Looking ahead, the LGC project could expand beyond this community and become a tool to build upon within the industrial or academic sectors. The journey includes many challenges on technical, quality assurance and workflow aspects. Most of these will not be fully resolved when the first open-source version of LGC is released, but with the help and support of the recently created CERN Open Source Program Office it is hoped that they can be gradually overcome. The development team anticipates making LGC available to external users by the end of 2024.

ACKNOWLEDGEMENTS

The authors extend heartfelt thanks to the multitude of individuals who have contributed to and tested SurveyLib, LGC, and SurveyPad over the past forty years. While it is impossible to individually name all who have left their mark, we deeply appreciate every contribution.

REFERENCES

[1] P. Lewandowski, R. Ducceschi, and F. Klumb, "SurveyPad, a common interface to Geode & data processing tools", IWAA 2022, CERN, Switzerland, Oct. 2022.

[2] P. Sainvitu, P. Dewitte, J. Gayde, D. Mergelkuhl, and D. Missiaen, "Tsunami, a Unified In-Field Measurement and Alignment Software for Experiments and Accelerators at CERN Large Scale Metrology Section", IWAA 2016, ESRF, France, Oct. 2016.

[3] A.-V. Naegely, I. Iliev, and A. Bensahla Talet, "GEODE: A new database interface with apex", IWAA 2016, ESRF, France, Oct. 2016.

[4] J. Gutekunst, F. Klumb, G. Kautzmann, H. Mainaud Durand, and M. Sosin, "Continuous position estimation for the full remote alignment system of the High Luminosity LHC upgrade", *JACoW*, vol. IPAC2024, THPG36, 2024. doi:10.18429/JACoW-IPAC2024-THPG36

[5] H. Mainaud Durand and D. Martin, "Towards a European community for Accelerators, Detectors and Beamline alignment", IWAA 2024, SLAC, USA, Oct. 2024.

[6] J. K. Iliffe, "Three-dimensional adjustments in a local reference system", CERN, Tech. Rep., 1987. https://cds.cern.ch/record/611257

[7] M. Jones, "An object oriented approach to processing accelerator alignment measurements", IWAA 2010, DESY, Germany, Sep. 2010.

[8] M. Barbier, Q. Dorleat, and M. Jones, "LGC: a new revised version", IWAA 2016, ESRF, France, Oct. 2016.

[9] N. Ibarrola and M. Jones, "Analysis and Evaluation of the CERN Reference Systems", IWAA 2016, ESRF, France, Oct. 2016.

[10] P. Valentin, J.-F. Fuchs, and F. Klumb, "Development of SMART: a stand-alone software for data acquisition at CERN", IWAA 2018, FERMILAB, USA, Oct. 2018.

[11] P.-A. Sanglier, P. Lewandowski, and F. Klumb, "First experience on python development for survey software, advantages and drawbacks", IWAA 2016, ESRF, France, Oct. 2016.

[12] C. Vendeuvre and L. Hadj Kaci, "A new process for calculating beam offsets during alignment", IWAA 2024, SLAC, USA, Oct. 2024.

[13] J.-F. Fuchs, J.-F. Segers, and C. Vendeuvre, "Development of a new levelling process integrated into a 3D global calculation", IWAA 2024, SLAC, USA, Oct. 2024.

[14] V. Rude, G. Kautzmann, H. Mainaud Durand, A. V. Naegely, M. Sosin, and M. Udzik, "3D calculation for the alignment of LHC low-beta quadrupoles", IWAA 2022, CERN, Switzerland, Oct. 2022.

[15] G. Kautzmann, J. Gayde, and F. Klumb, "HIE-ISOLDE: Commissioning and first results of the Mathilde system monitoring the positions of cavities and solenoids inside cryomodules", IWAA 2016, ESRF, France, Oct. 2016.

[16] F. Barcet, D. Mergelkuhl, and P. Bestmann, "Direct wire offset measurements by photogrammetry including a gravity link", IWAA 2024, SLAC, USA, Oct. 2024.

[17] L. Watrelot, "FCC-ee Machine Detector Interface Alignment System Concepts", Ph.D. dissertation, Paris U., VI-VII, 2023.

[18] L. Watrelot, B. Weyer, and W. Niewiem, "Status of geodetic studies and alignment perspectives for the CERN Future Circular Collider", IWAA 2024, SLAC, USA, Oct. 2024.

[19] *Jira*, https://its.cern.ch/jira/.

[20] *Gitlab*, https://gitlab.cern.ch/.

[21] *Openstack*, https://openstack.cern.ch/.

[22] "CERN Open Science Policy", CERN, Tech. Rep., 2022. doi:10.17181/CERN.RTIF.Z8BO

[23] S. Durand, T. Touzé, M. Jones, S. Guillaume, P. H. Cattin, and L. Morel, "Evaluation of Compatibility among Network Adjustment Software: CoMeT, LGC, and Trinet+", *J. Survey. Eng.*, vol. 146, no. 2, p. 04 020 005, 2020. doi:10.1061/(asce)su.1943-5428.0000304

[24] "Mandate for the CERN Open Source Program Office (OSPO)", CERN, Tech. Rep., 2023. https://cds.cern.ch/record/2879995

[25] F. Fluckiger, "Final Report of the Open Source Software Licence Task Force", CERN, Tech. Rep., 2012. https://cds.cern.ch/record/1482206

[26] *Spatial analyzer*, https://www.kinematics.com/spatialanalyzer/.